# Physics Issues for the ILC

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ILC PAC meeting
November 2010

1. What is the essential physics case for the ILC ?

2. What can the LHC teach us in 2011 ?

3. What ILC energy will we need after the LHC ?

basic elements of the physics program of the ILC:

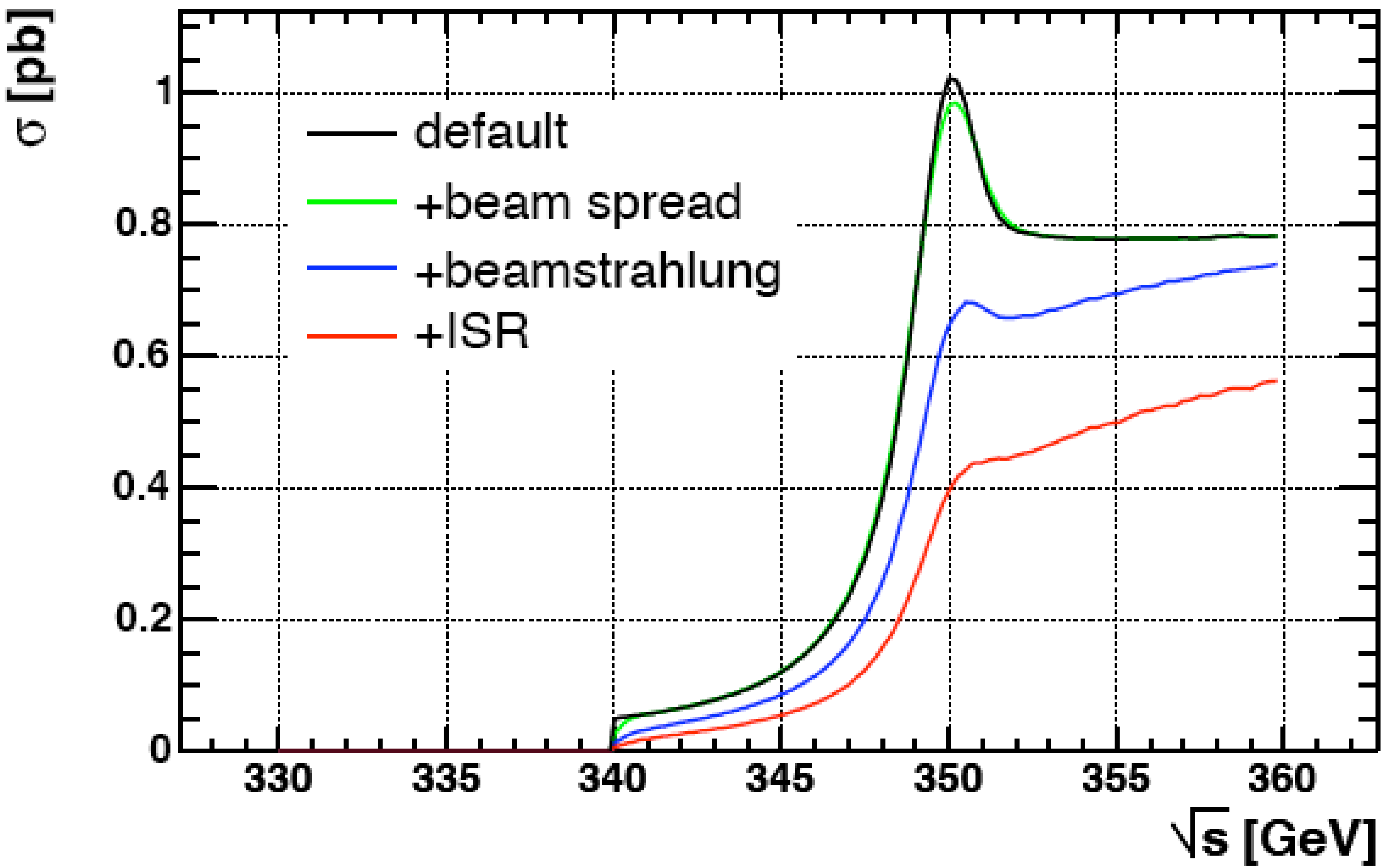
1. Precision measurements of $e^+e^- \to f\overline{f}$
   relevant to Z' models, extra dimensions, compositeness

2. Precision measurements of $e^+e^- \to W^+W^-$
   relevant to strongly interacting Higgs sectors

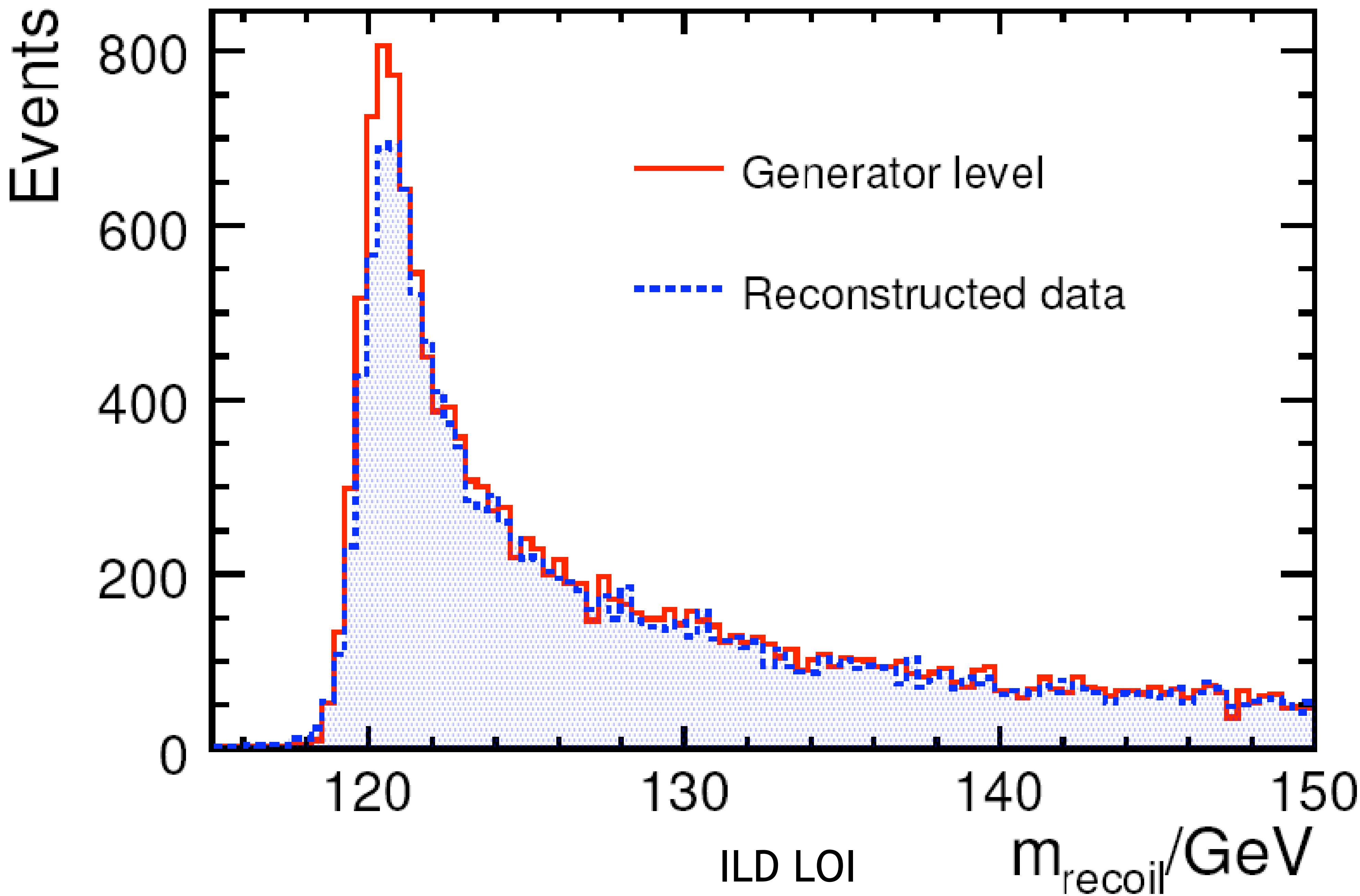
3. Precision measurements of $m_t$ and $e^+e^- \to t\bar{t}$
   relevant to precision electroweak and/or
   strongly interacting sectors with Higgs and top

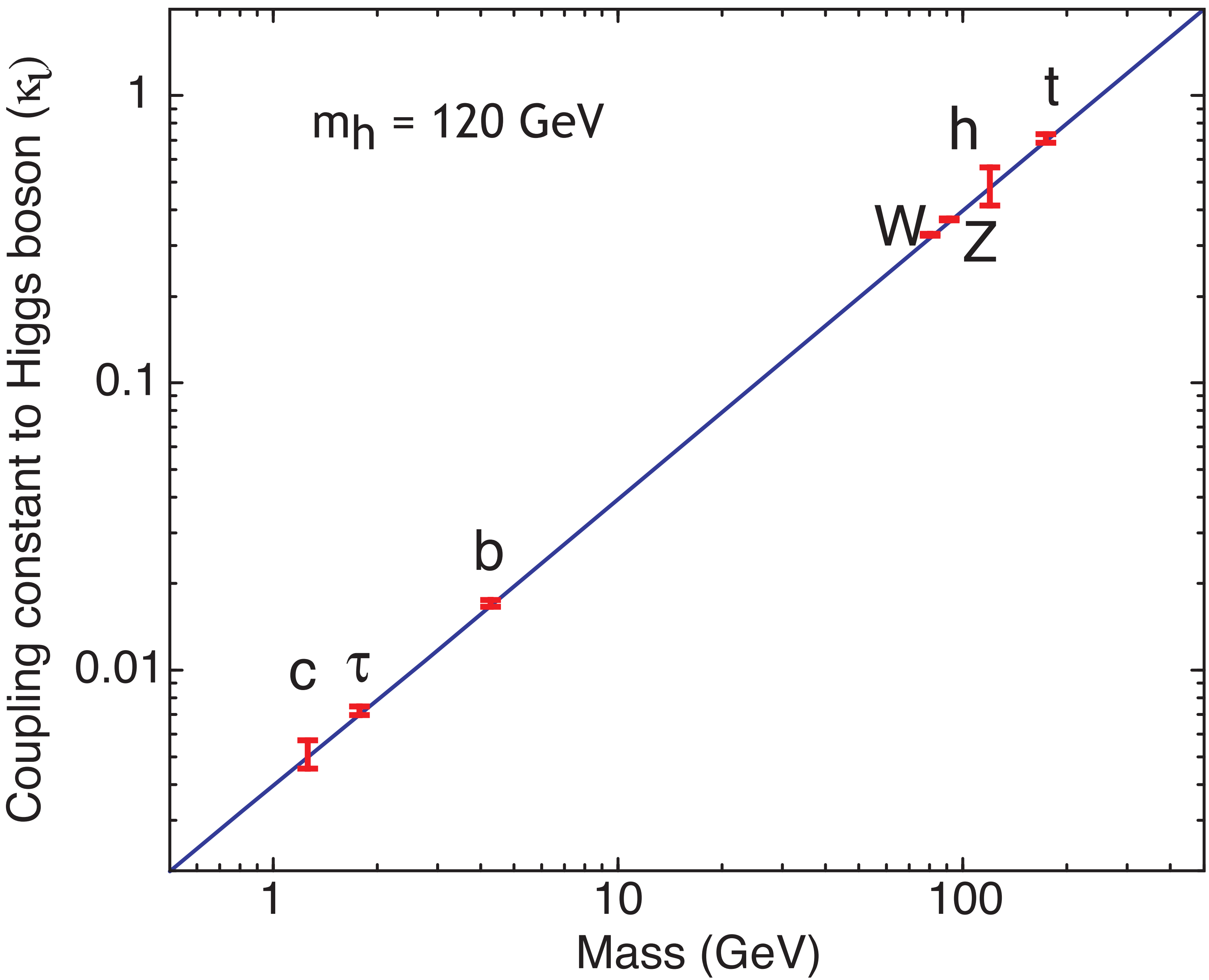
4. Precision measurements of the Higgs boson couplings
   testing whether this particle actually gives 100% of the
   mass of all quarks, leptons, and bosons

5. And, for any new particles discovered or suggested by LHC
   their detailed characterization and measurement of
   quantum numbers -- and relevance to cosmic dark matter

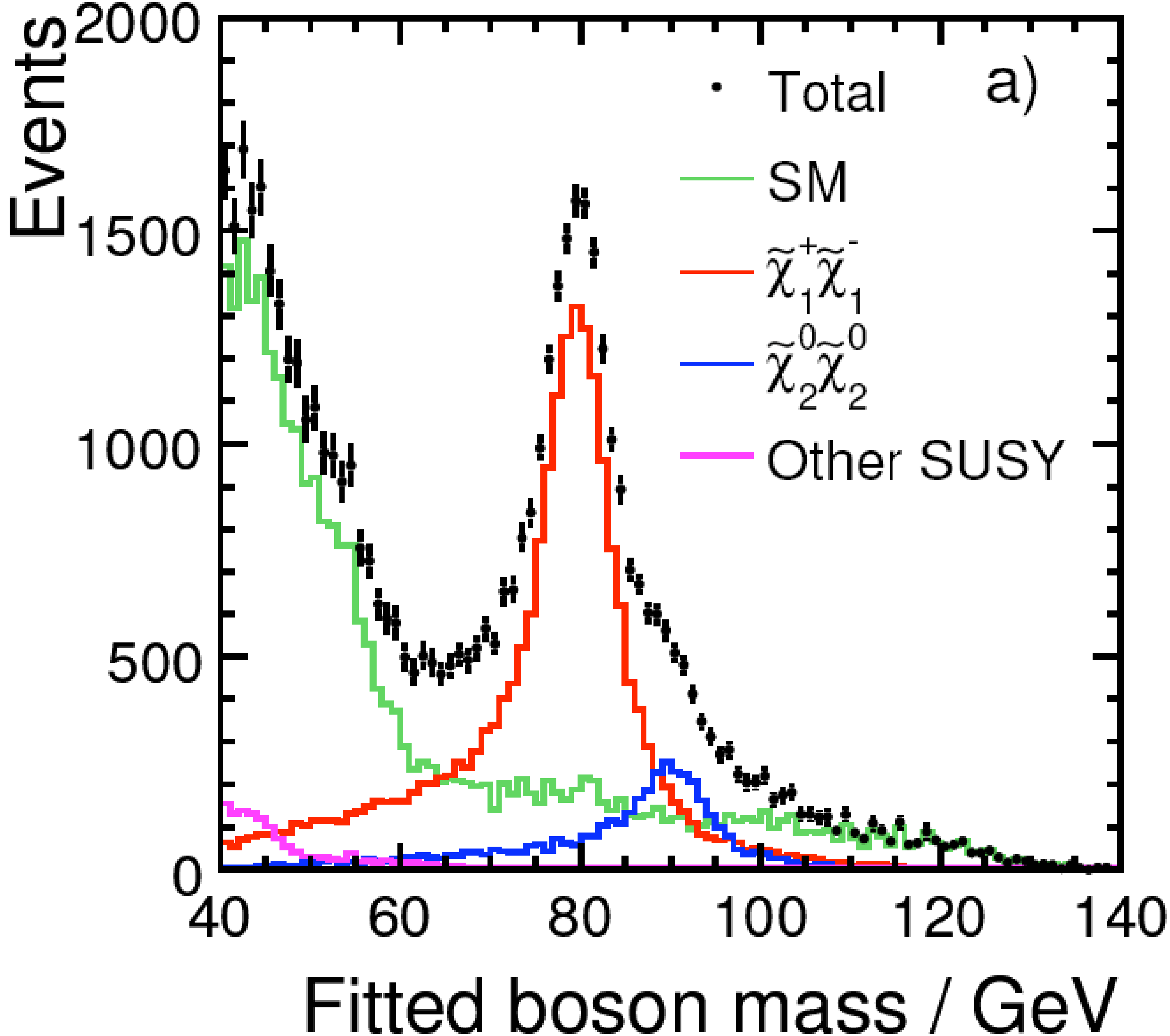

σ [pb]
1
0.8
0.6
0.4
0.2
0
default
+beam spread
+beamstrahlung
+ISR
330
335
340
345
350
355
360
√s [GeV]

Higgs recoil mass distribution



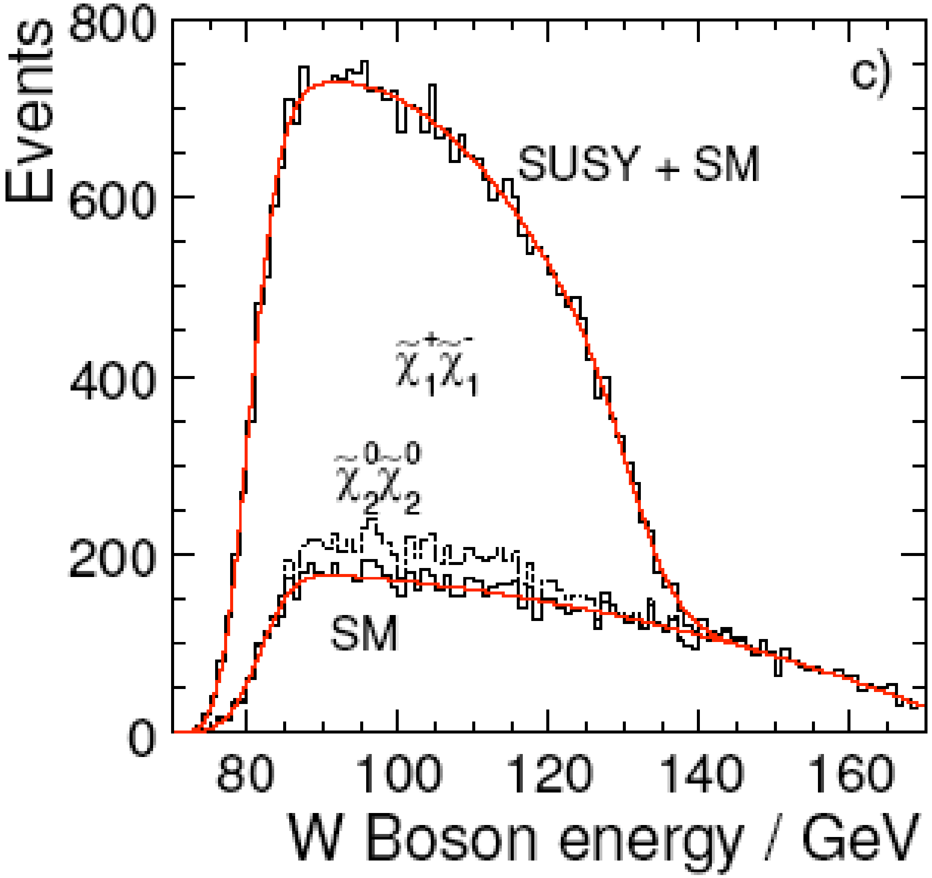


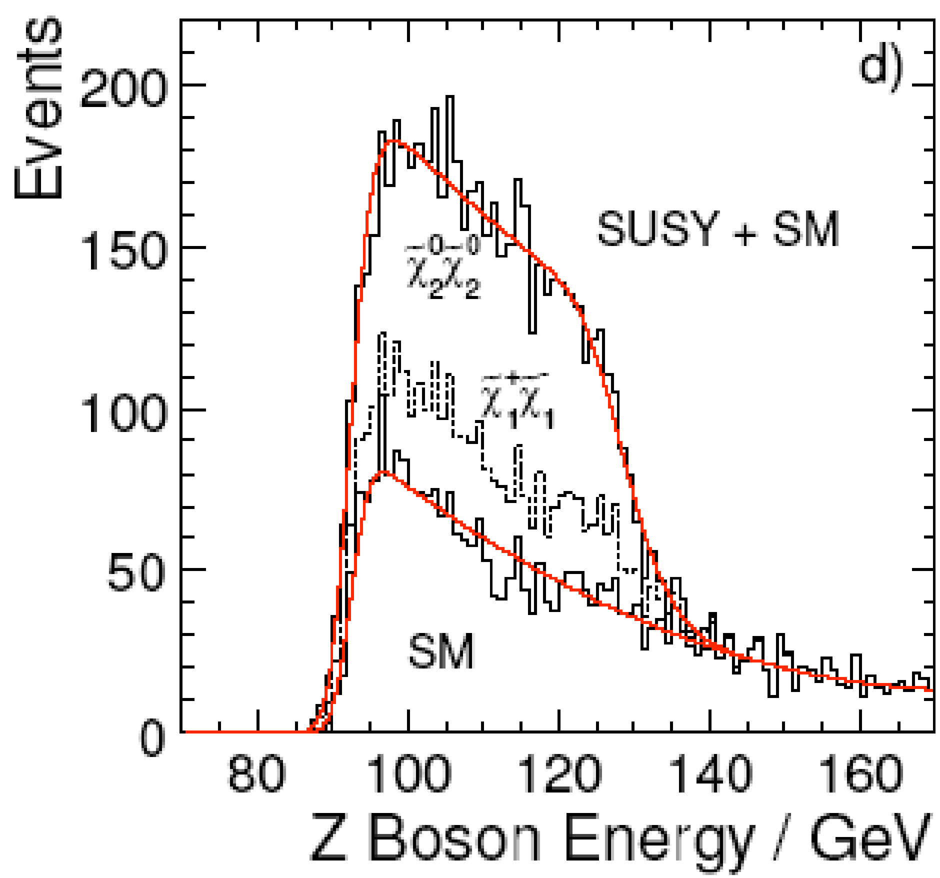
ACFA LC study


Events
2000
1500
1000
500
0
40
60
80
100
120
140
Fitted boson mass / GeV
Total
a)
SM
$\tilde{\chi}_1^+\tilde{\chi}_1^-$
$\tilde{\chi}_2^0\tilde{\chi}_2^0$
Other SUSY

ILD
LOI

W and Z boson energy distributions
in chargino/neutralino pair production

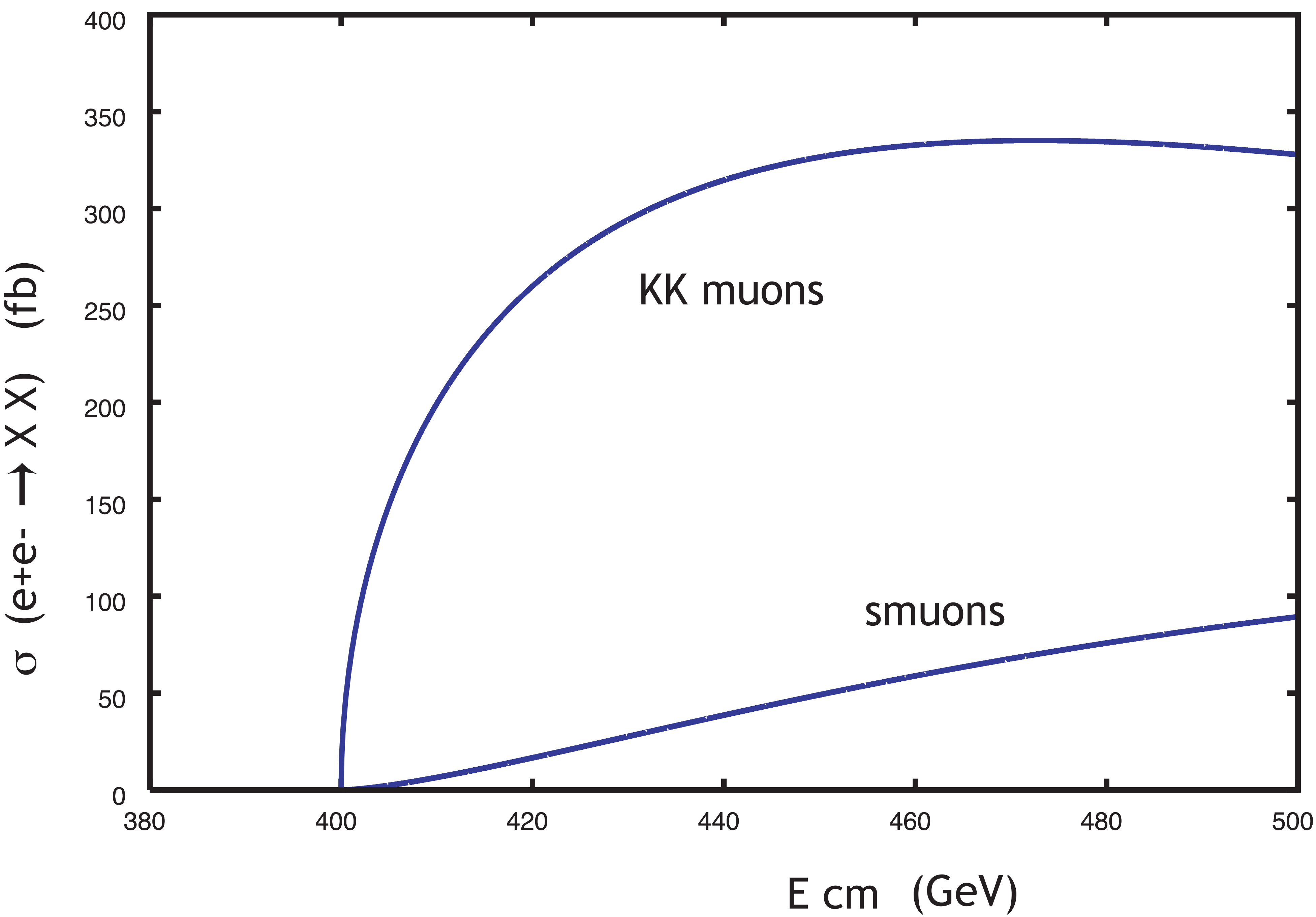



ILD LOI

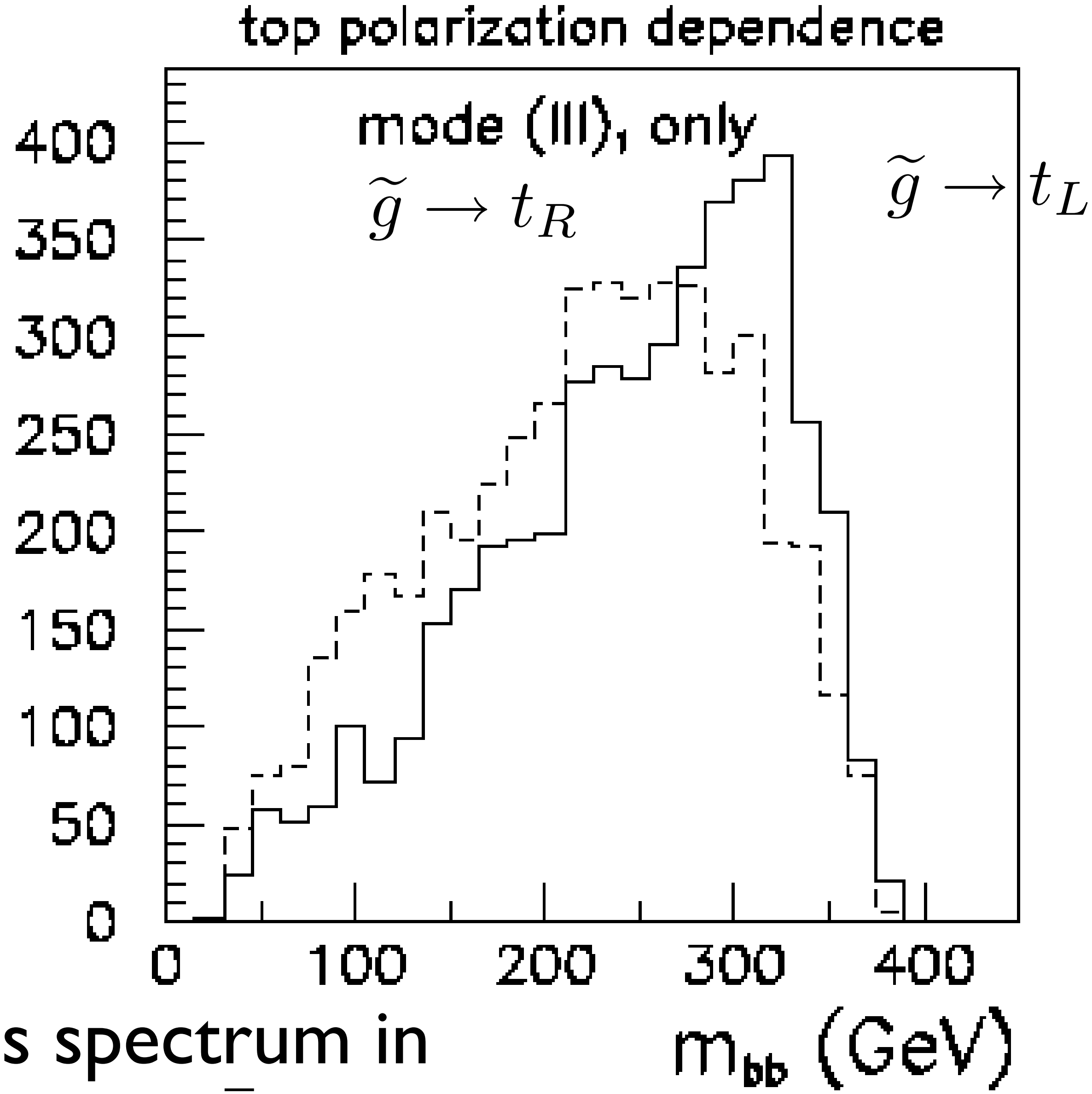
The idea of this program is to explore the same new fundamental interactions that will be studied at the LHC,

but to move qualitatively beyond the capabilities of the LHC experiments.



400
350
300
250
200
150
100
50
0
380
400
420
440
460
480
500
KK muons
smuons
$\sigma$ (e+e- $\rightarrow$ X $\bar{X}$) (fb)
E cm (GeV)

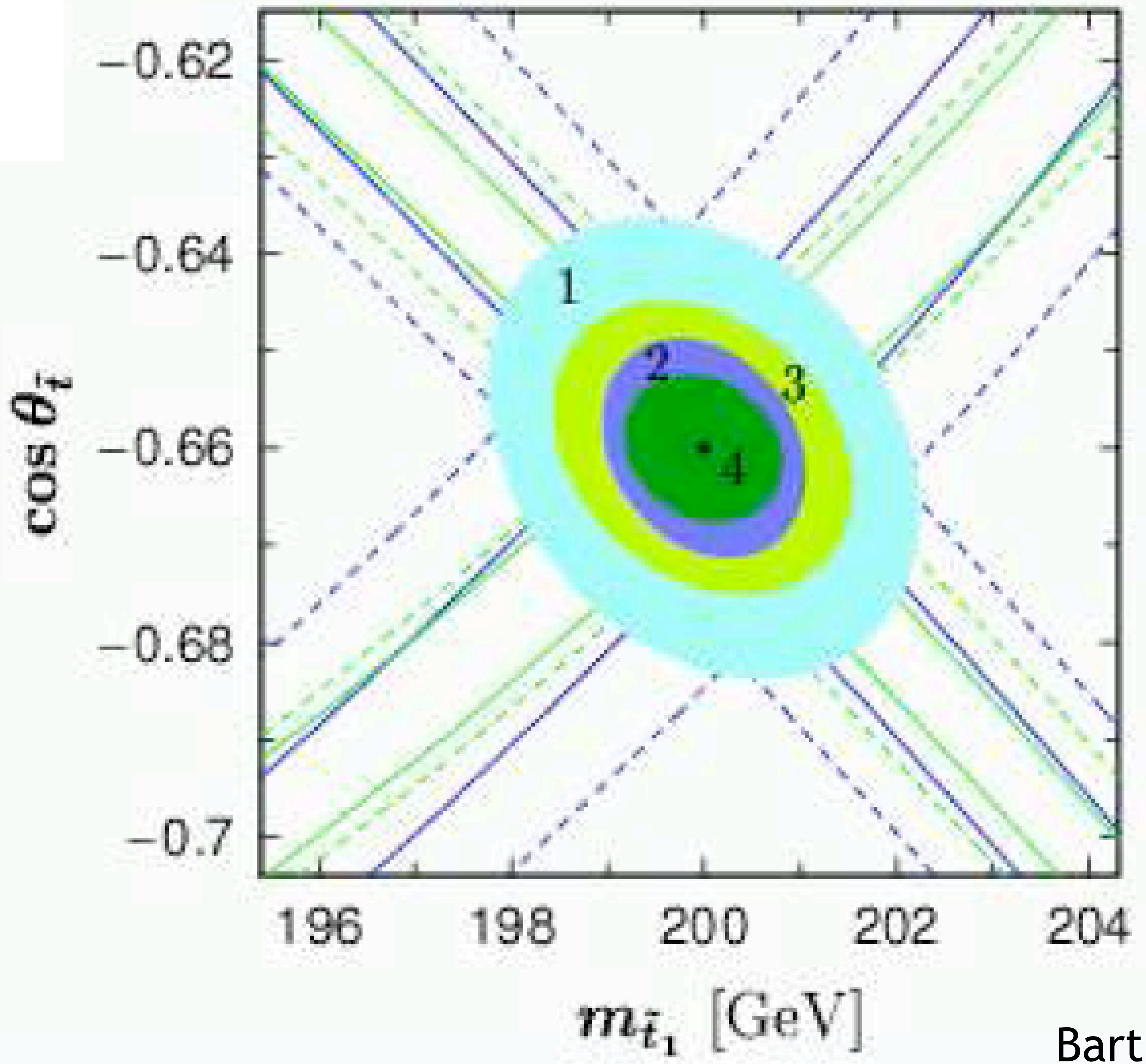
For example, if there is a light top squark, is it the partner of the tL or the tR ?




bb mass spectrum in

$\widetilde{g} \to t\bar{b}\chi^- \to b\bar{b} + X$

Hisano, Kawagoe, Nojiri



−0.62
−0.64
−0.66
−0.68
−0.7
$\cos\theta_{\tilde{t}}$
196
198
200
202
204
$m_{\tilde{t}_1}$ [GeV]
1
2
3
4


Bartl et al.

BUT,

this is all about hypothetical particles and forces.

To the general public, even the Higgs boson is hypothetical ...

When will we get concrete evidence of new physics beyond the Standard Model ?

It is unfortunately possible that this information will not come soon.

To discover a light Standard Model Higgs boson (m ~ 120-130 GeV) at the LHC requires of order 10 fb-1 at 14 TeV. We might not have this until 2014.

There are many scenarios for physics beyond the Standard Model in which this will be the first new object seen at the LHC.

However ...

The LHC machine physicists are currently optimistic about 2011.

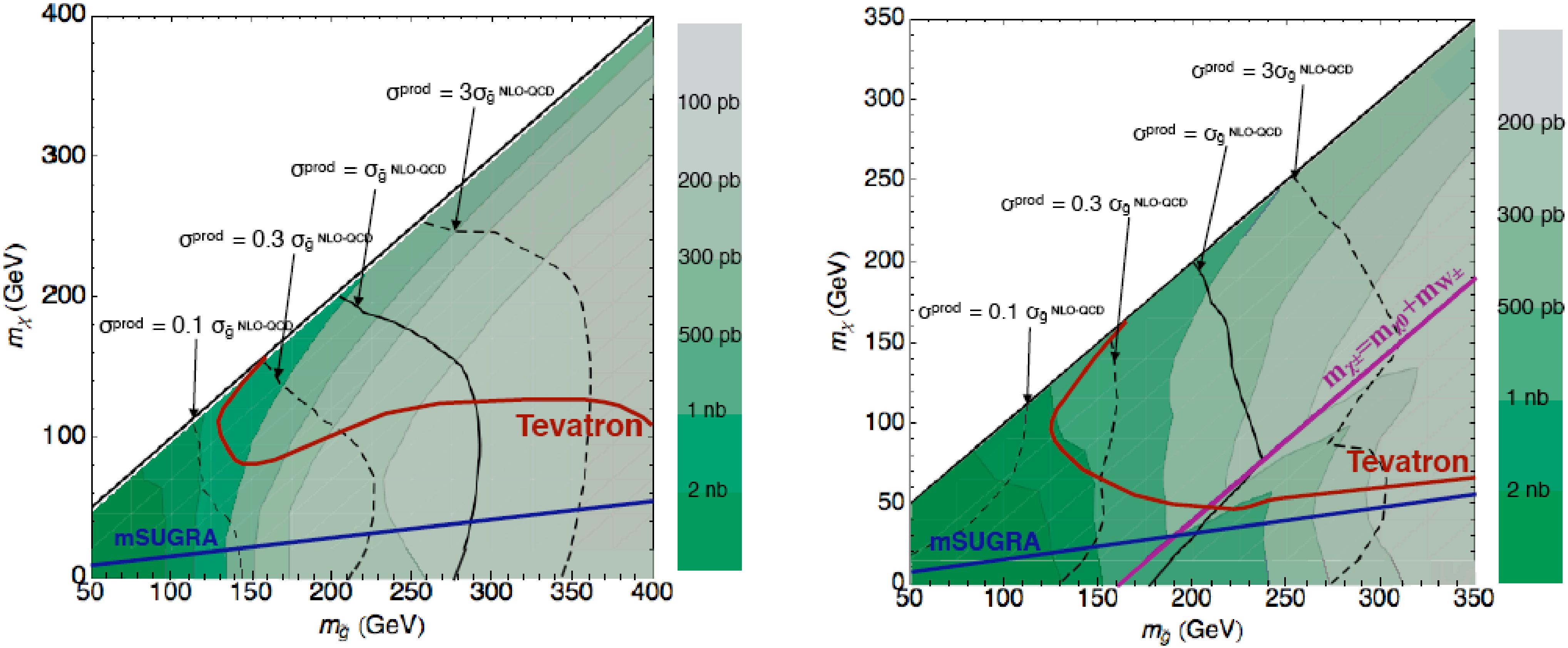
1.5 pb-1/day has been achieved.  Another large factor in luminosity is available by filling 10x more buckets. This makes it likely that one can meet the 2010 goal of 1 fb-1 at 7 TeV.

It is possible that LHC will run beyond 2011 at 7 - 10 TeV.

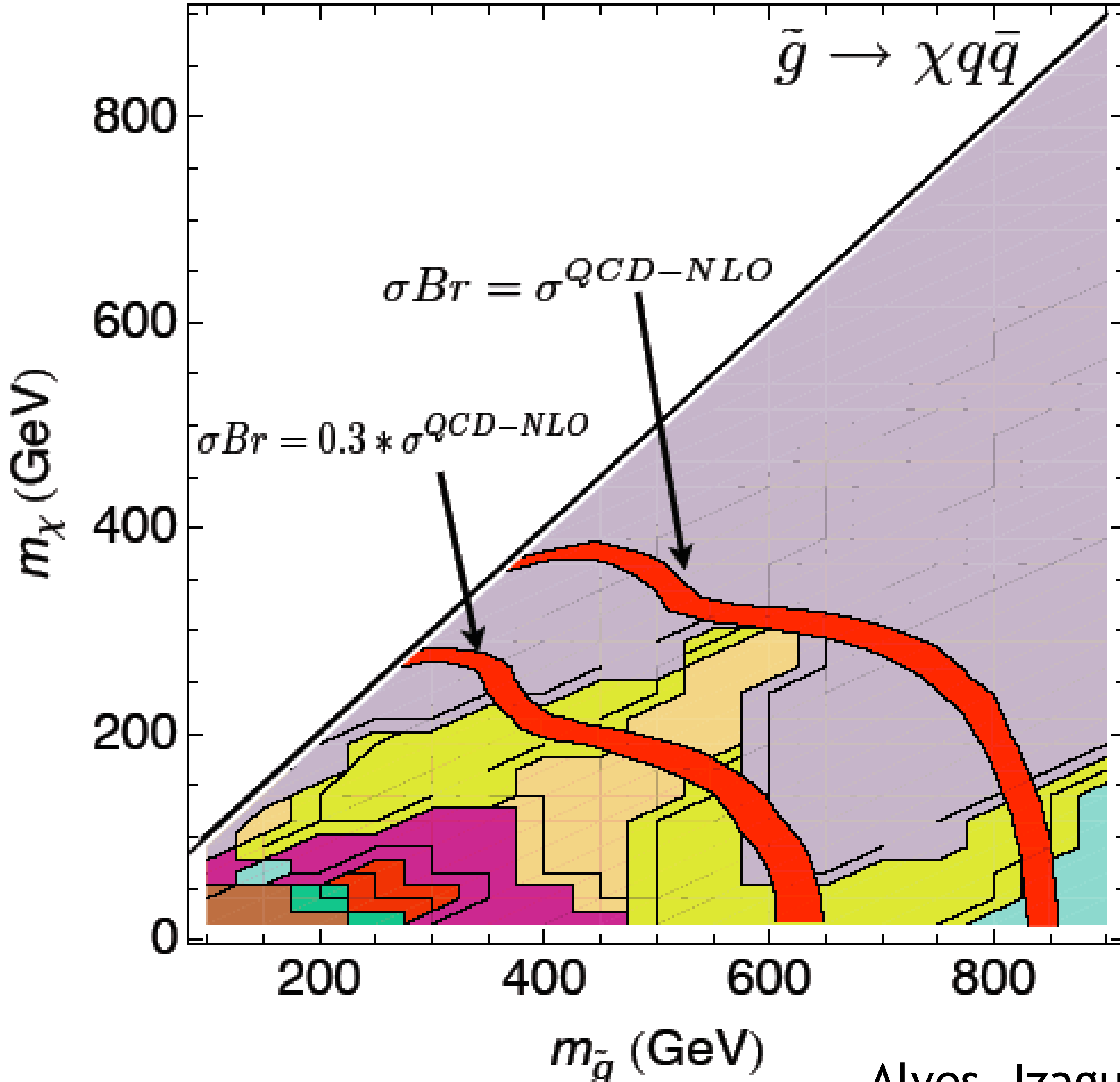
and

The nominal program of 1 fb-1 at 7 TeV can already access interesting physics models:

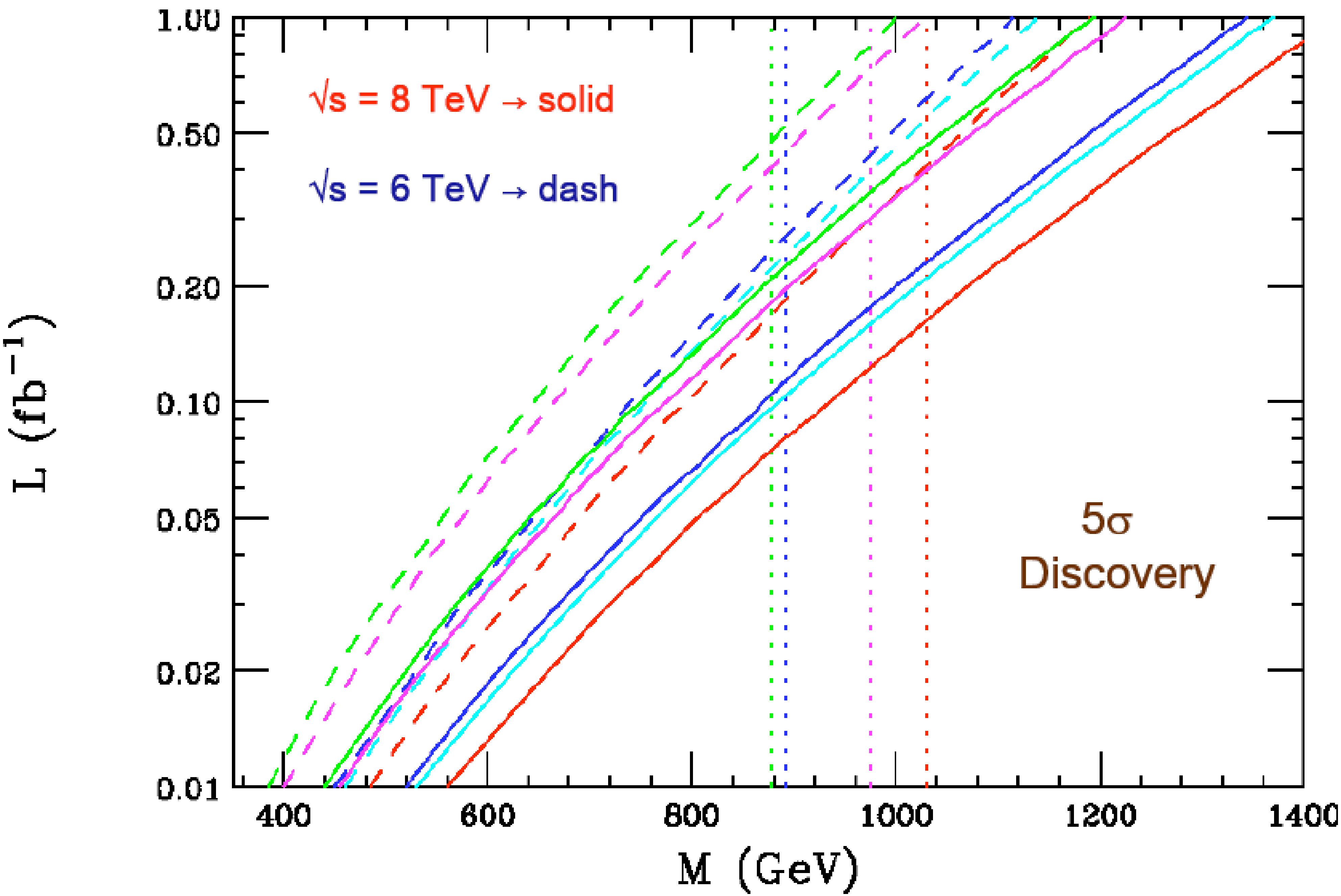
1. Supersymmetry or other new particle production.
2. Z' resonances.
3. top quark resonances.




Alves, Izaguirre, Wacker



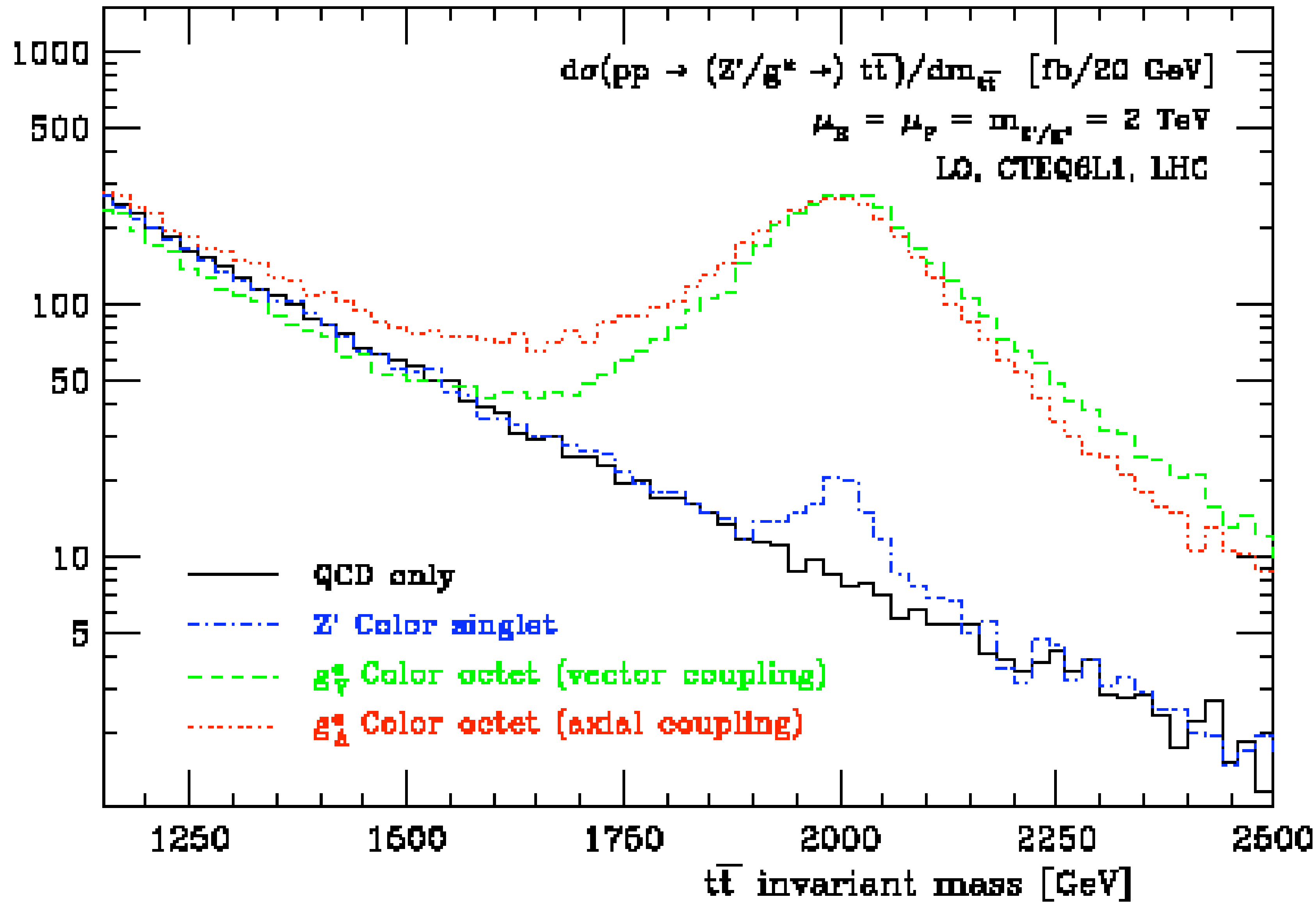

Alves, Izaguirre, Wacker



√s = 8 TeV → solid
√s = 6 TeV → dash
5σ
Discovery
L (fb$^{-1}$)
M (GeV)
1.00
0.50
0.20
0.10
0.05
0.02
0.01
400
600
800
1000
1200
1400


Rizzo

topcolor gluons




Maltoni, Frederix

LHC is expected to discover new fundamental particles and interactions, either in 2011 or later.

When these discoveries are made, we will certainly argue for new tools to fully understand these new forces of Nature.

Esssential, tactile issues will be involved. In particular, it is very likely that the identity of the dark matter in the universe will be revealed at the 1 TeV energy scale.

A key issue for this discussion is:

What energy in e+e- do we need to follow up the discoveries at the LHC ?

At the ILC, we are discussing an energy of 500 GeV, extendable to 1 TeV.   The competitor technologies -- CLIC and Muon Collider -- aim for 3 TeV.

LHC will access masses in the multi-TeV region.

Isn’t higher energy always better ?

In thinking about this issue, it is very important to move your imagination forward to the era where discoveries have actually been made. We will no longer be engaged in a blind search for new physics. There will be new physics, and it will be mysterious. You need to ask:

What energy will be need to solve the mysteries ?

I hope that the HEP community will consider the questions raised by these discoveries to be of the highest importance. The solution of the mysteries will be urgent. Other scientists, politicians, and the public will want us to put a concrete proposal on the table. CLIC and Muon Collider will not be ready.

If we have the opportunity, should we go forward with ILC ?

Example of supersymmetry:

Eventually, the LHC will probe for SUSY over essentially all of the interesting parameter region. Most of the SUSY masses will be measured in SUSY cascade decays.

A role of the ILC will be to supply precision studies of the chargino, neutralino, and Higgs sectors. This information is needed for many issues, including, Is it really SUSY ?

What will we know about these after the 2011 run of the LHC ?

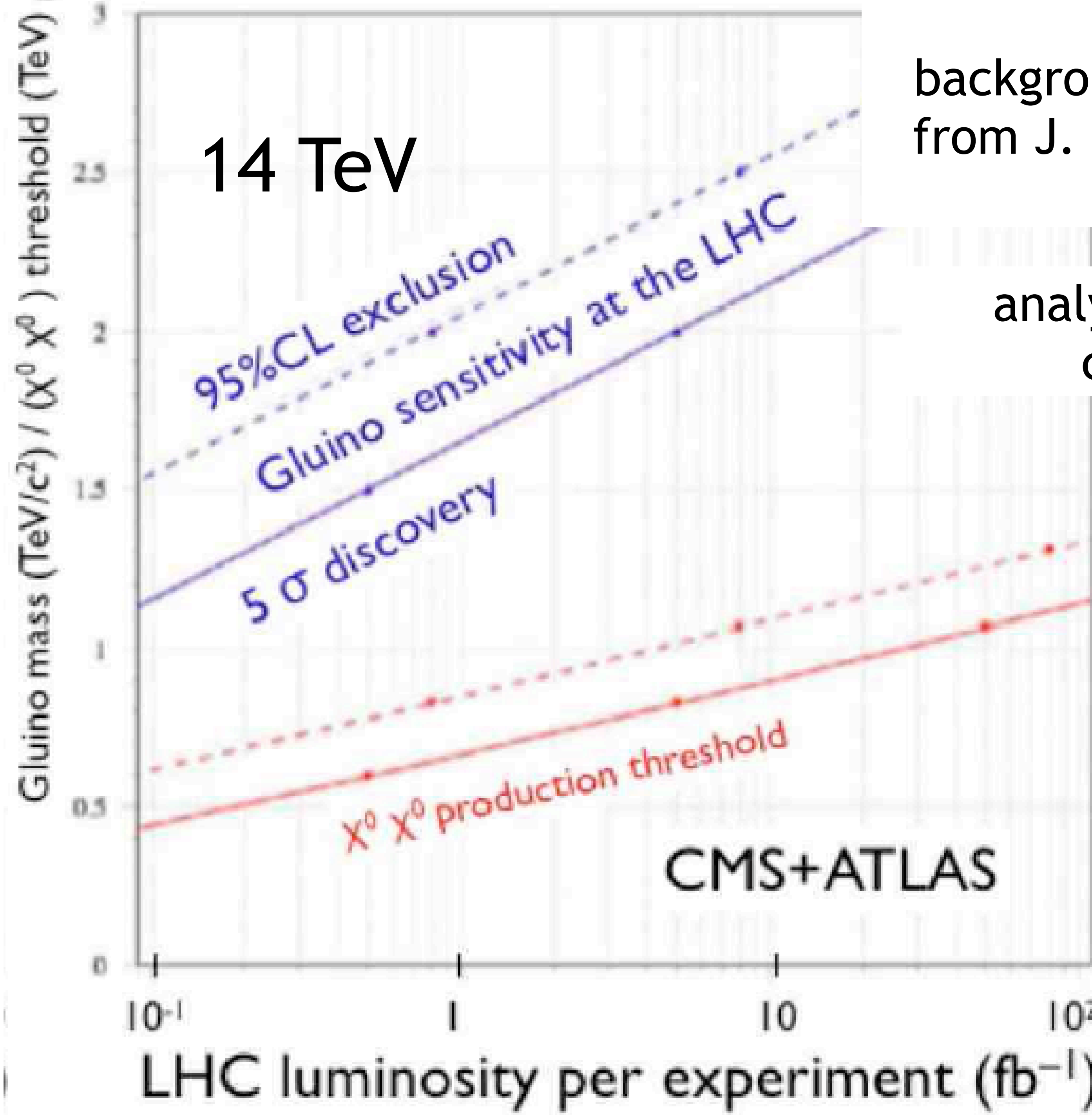
Only QCD pair prodution reactions will be strongly constrained. Inferences about the color singlet superparticles will come from "gaugino universality": $m(\widetilde{g}) \approx 3.5\, m(\widetilde{w}) \approx 7\, m(\widetilde{b})$

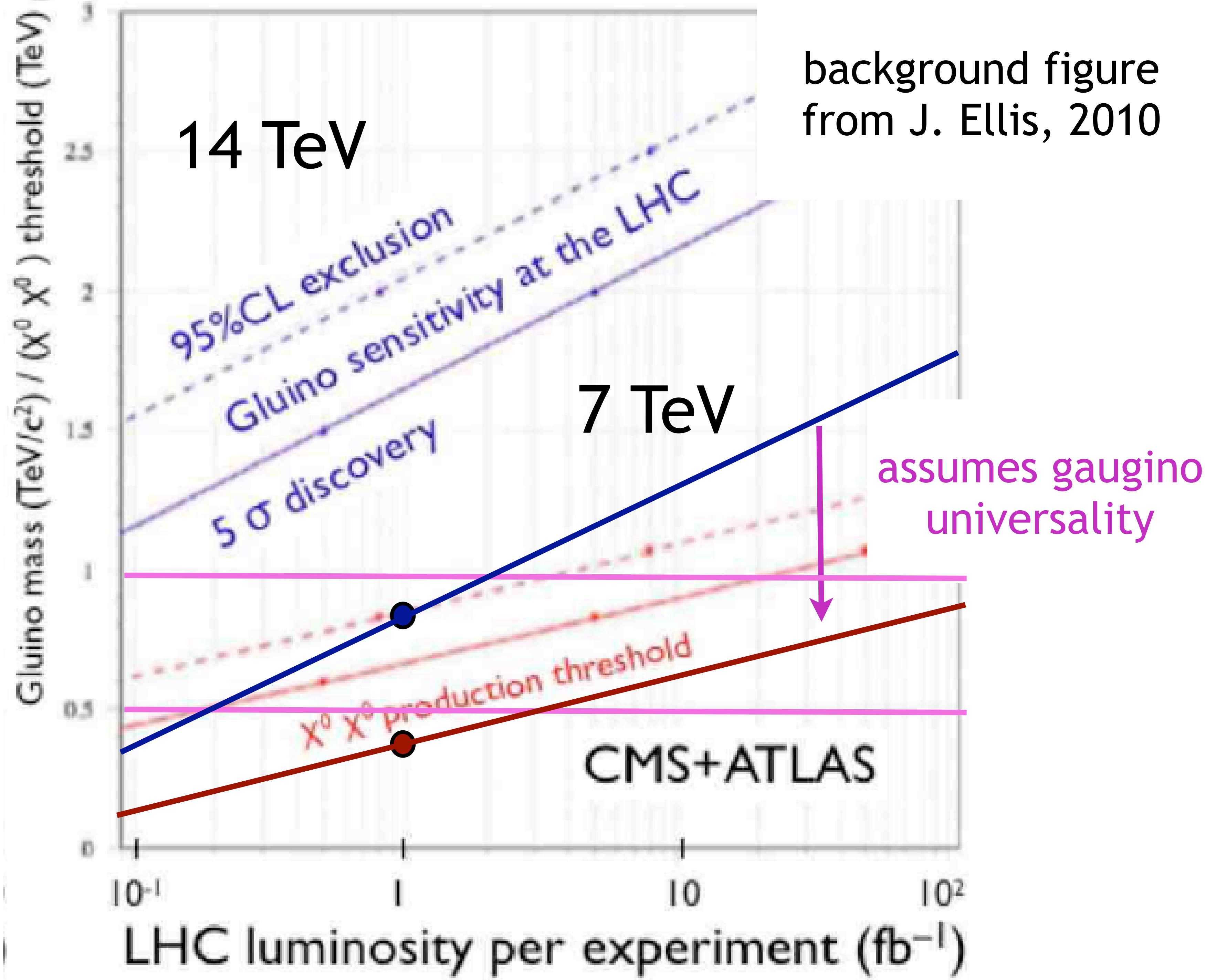
This relation is true in many benchmark models, but it is an assumption that is not well motivated theoretically. It is introduced as a simplification of the large SUSY parameter space.

14 TeV

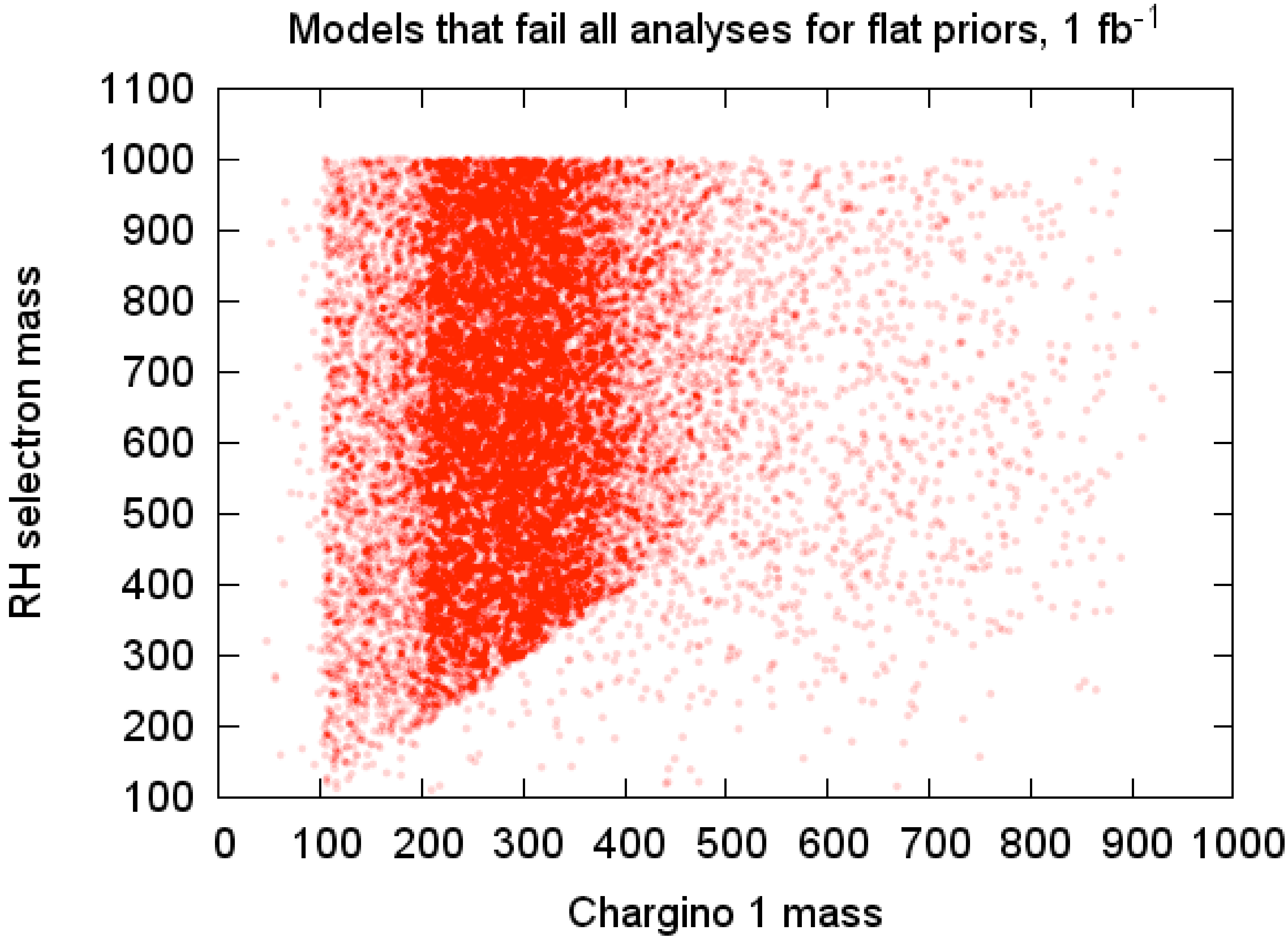
background figure from J. Ellis, 2010

analysis in the cMSSM





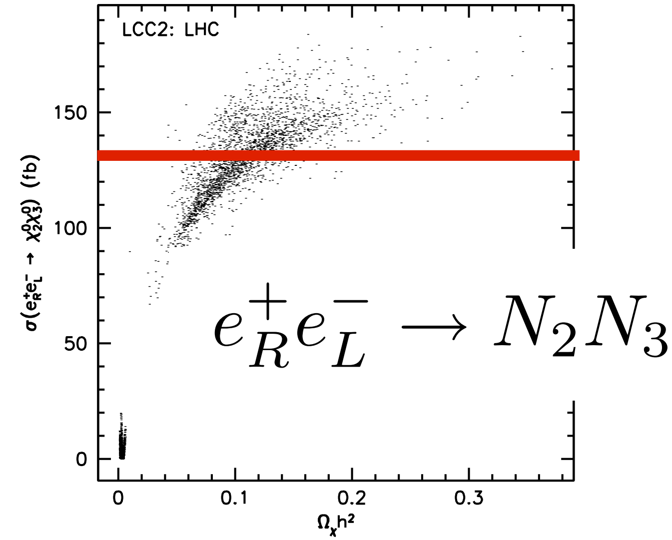

background figure from J. Ellis, 2010




Conley, Gainer, Hewett, Le, Rizzo

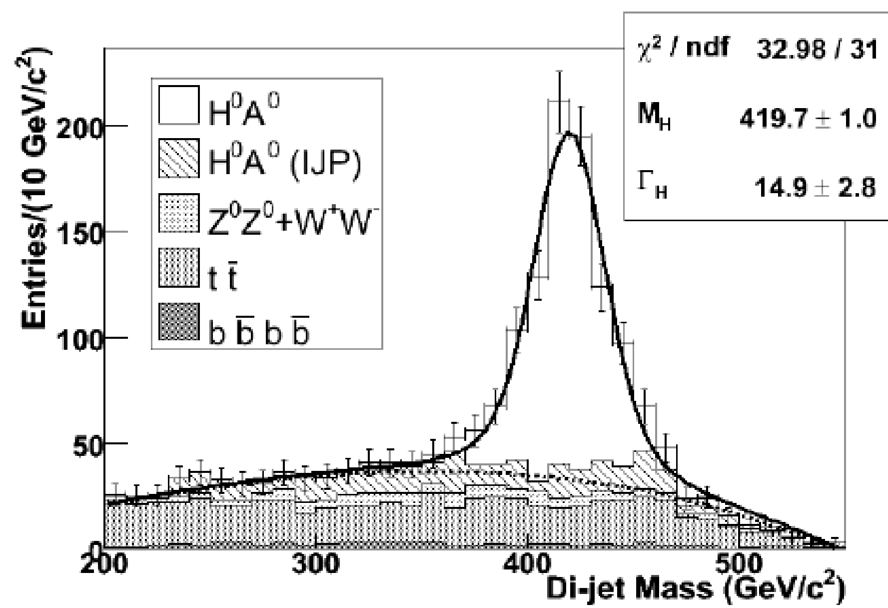
Why do we need to study neutralinos and Higgs bosons ? Here are two questions about supersymmetry that cannot be answered at the LHC:

Does the lightest neutralino really have the correct cross sections to be the dark matter particle?

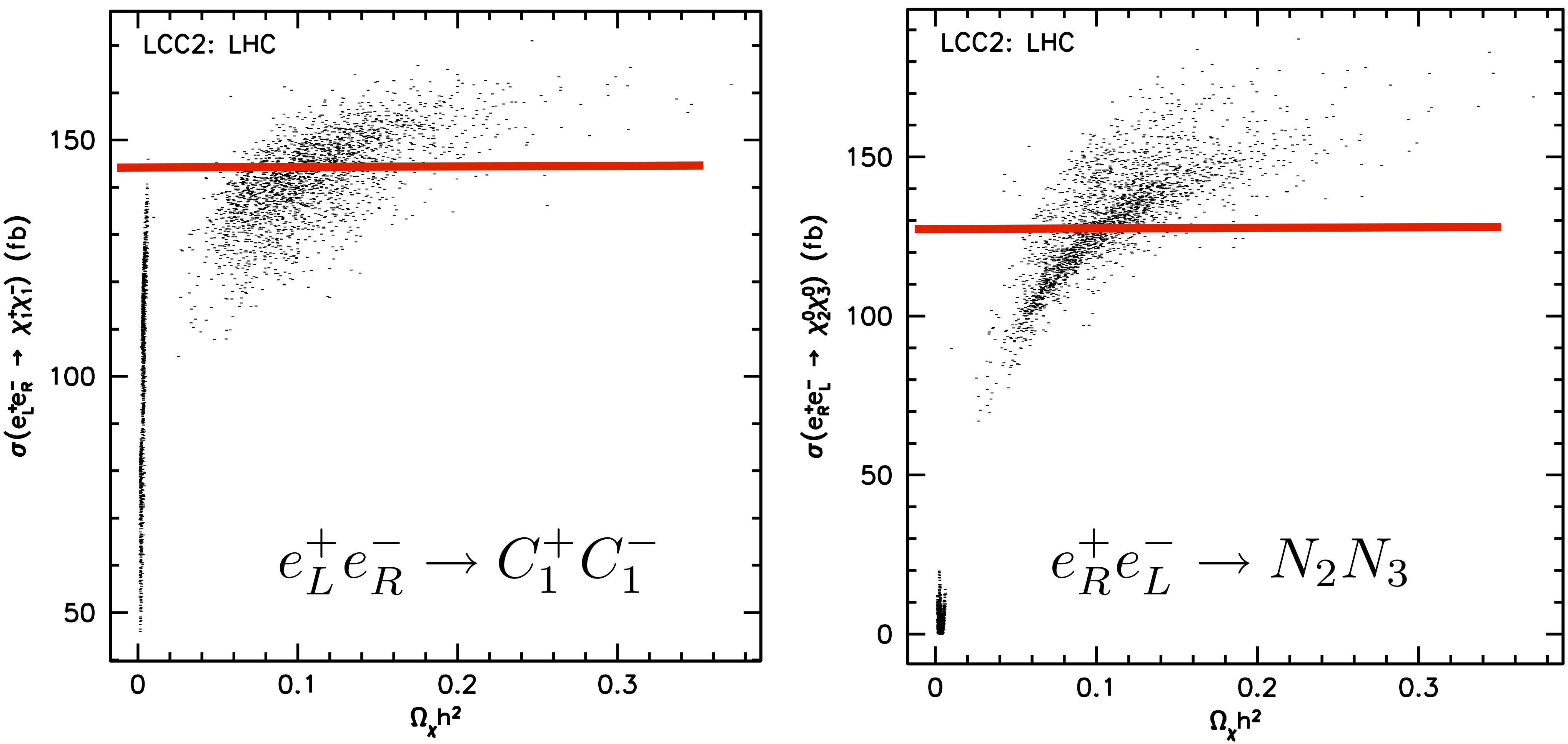



requires knowledge of the chargino/neutralino mixing angles and Higgs couplings

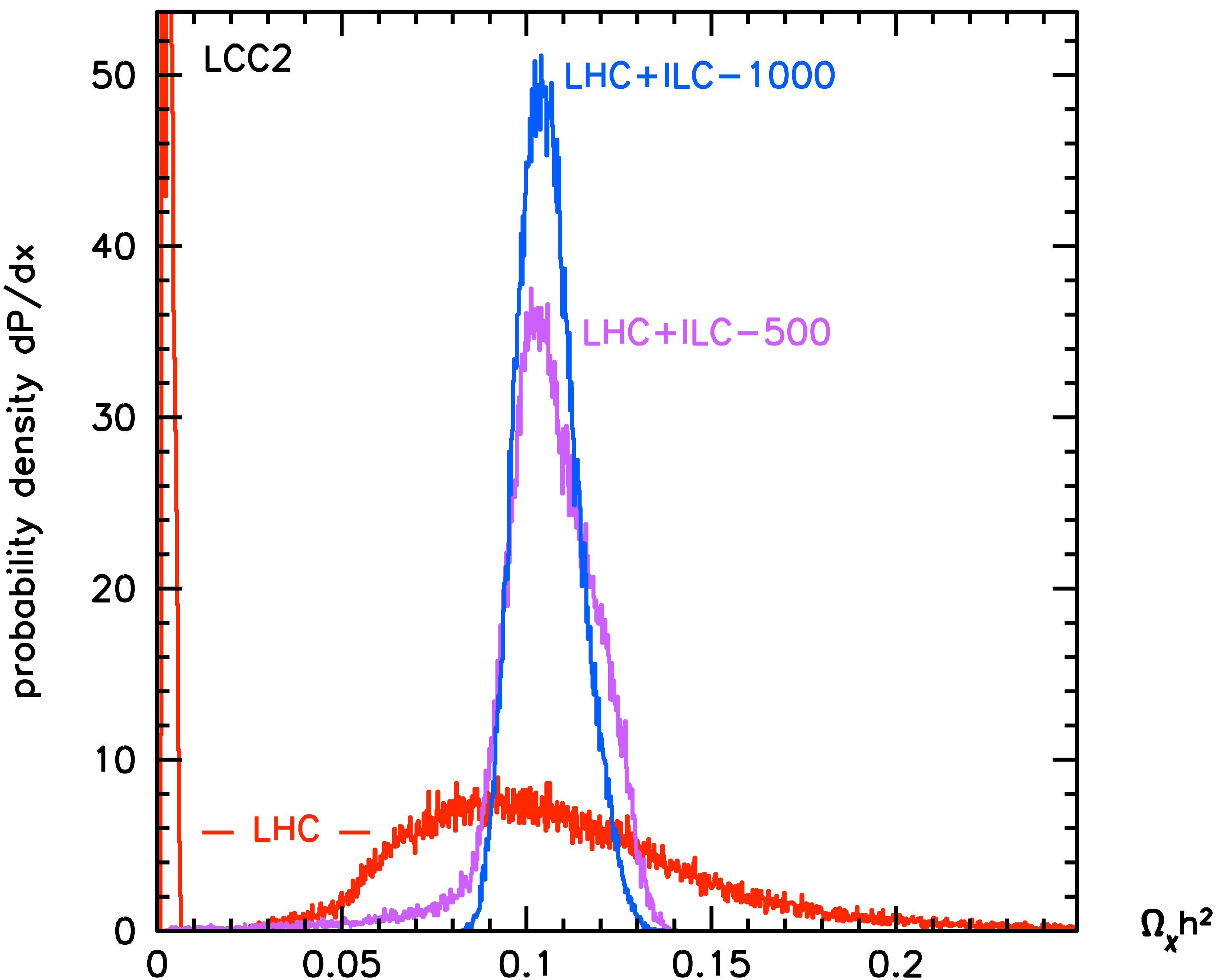
Does the stop/Higgs sector generate the potential that explains Higgs boson spontaneous symmetry breaking ?




requires knowledge of $\mu, \tan\beta$, and the stop mass matrix


LCC2: LHC
150
100
50
0
0.1
0.2
0.3
$\sigma(e^+_L e^-_R \to \chi^+_1 \chi^-_1)$ (fb)
$\Omega_\chi h^2$
$e^+_L e^-_R \to C^+_1 C^-_1$
LCC2: LHC
150
100
50
0
0
0.1
0.2
0.3
$\sigma(e^+_R e^-_L \to \chi^0_2 \chi^0_3)$ (fb)
$\Omega_\chi h^2$
$e^+_R e^-_L \to N_2 N_3$

Baltz et al.


LCC2
LHC+ILC−1000
LHC+ILC−500
— LHC —
probability density dP/dx
50
40
30
20
10
0
0.05
0.1
0.15
0.2
$\Omega_\chi h^2$

Baltz et al.

## Example of a Z’:

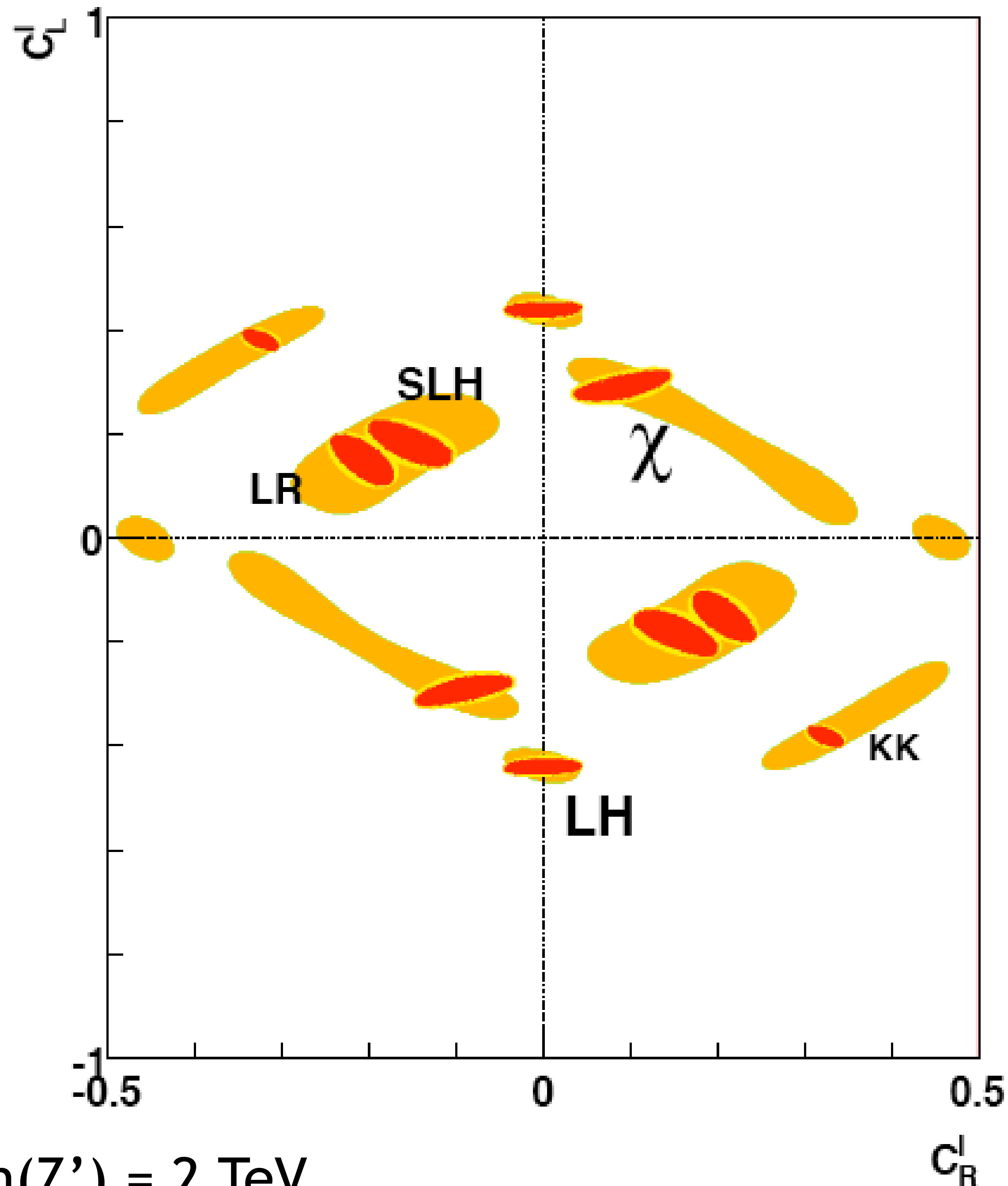
Ideally, we would like to go to the $Z'$ resonance. However, if there is no technology available for this, we can learn a great deal through polarized $e^+e^- \to f\overline{f}$ at the highest available energy.

For example, for $e^-_L e^+_R \to f_L \overline{f}_R$ , the $Z'$ adds an amplitude

$$\frac{g_{eL} \cdot g_{fL}}{s - m_Z^2 + i m_Z \Gamma_Z}(1+\cos\theta)$$

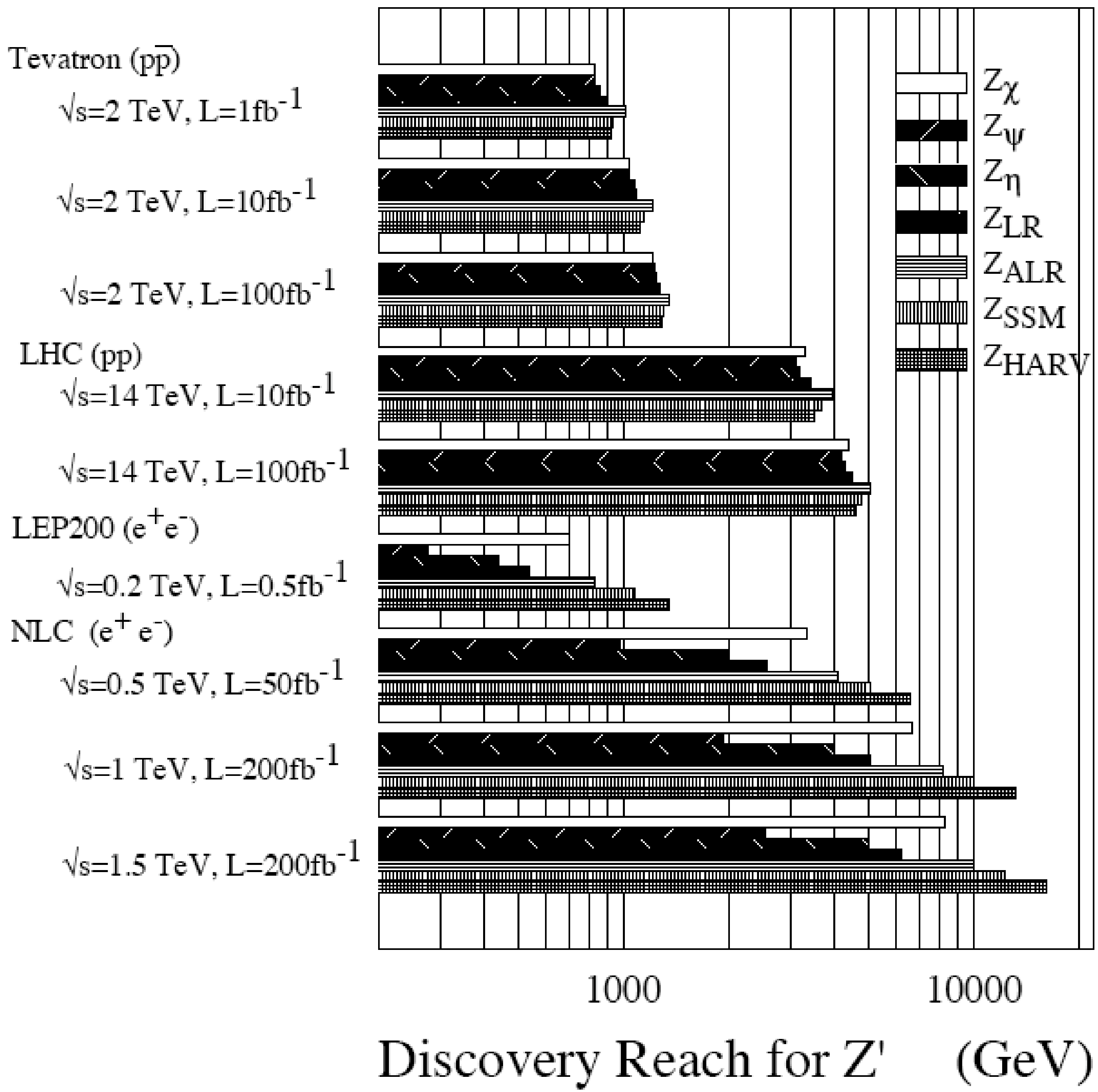
which interferes with the Standard Model pair-production amplitude. Using the mass from the LHC, we can use the polarized forward and backward cross sections to obtain all of the $Z'$ couplings. Many reactions are available:

$$\begin{aligned} e^+e^- &\to e^+e^-, \mu^+\mu^-, \tau^+\tau^- \\ e^+e^- &\to q\overline{q}, c\overline{c}, b\overline{b} \end{aligned}$$




500 GeV, m(Z’) = 2 TeV
1 ab-1, $e^+e^- \to \mu^+\mu^-$

Godfrey, Kalyniak, Tomkins



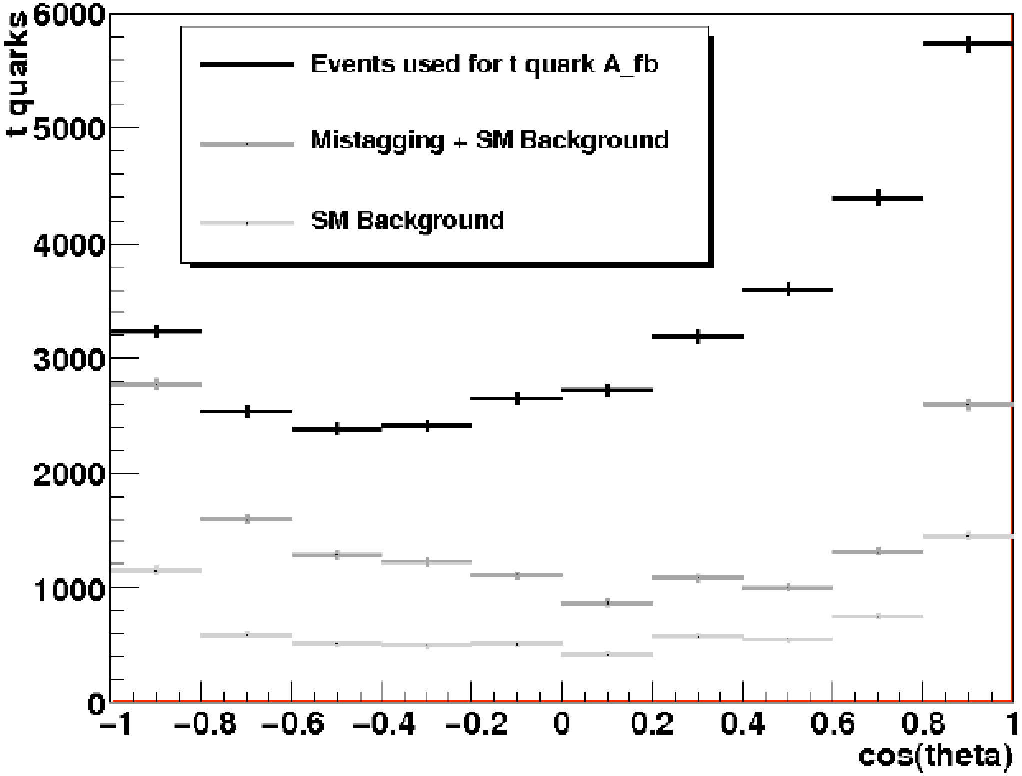
Tevatron (p$\bar{p}$)
$\sqrt{s}$=2 TeV, L=1fb$^{-1}$
$\sqrt{s}$=2 TeV, L=10fb$^{-1}$
$\sqrt{s}$=2 TeV, L=100fb$^{-1}$
LHC (pp)
$\sqrt{s}$=14 TeV, L=10fb$^{-1}$
$\sqrt{s}$=14 TeV, L=100fb$^{-1}$
LEP200 ($e^+e^-$)
$\sqrt{s}$=0.2 TeV, L=0.5fb$^{-1}$
NLC ($e^+ e^-$)
$\sqrt{s}$=0.5 TeV, L=50fb$^{-1}$
$\sqrt{s}$=1 TeV, L=200fb$^{-1}$
$\sqrt{s}$=1.5 TeV, L=200fb$^{-1}$
$Z_\chi$
$Z_\psi$
$Z_\eta$
$Z_{LR}$
$Z_{ALR}$
$Z_{SSM}$
$Z_{HARV}$
1000
10000
Discovery Reach for Z' (GeV)

## Example of top quark dynamics:

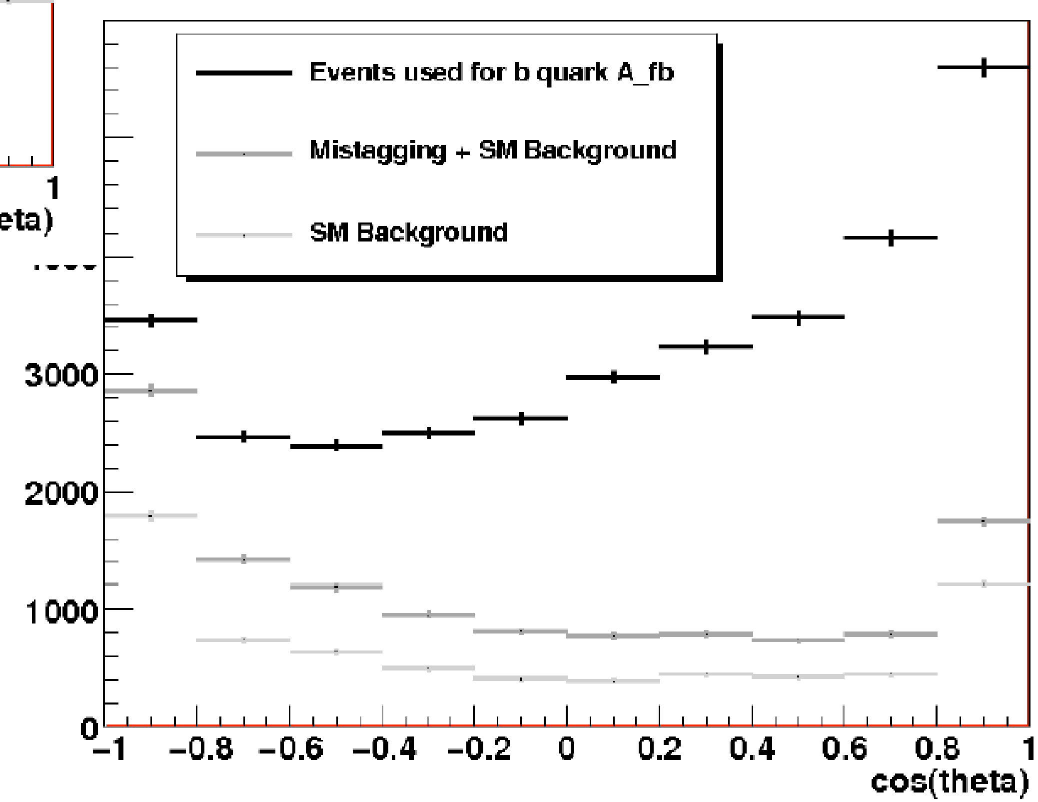
The top quark may be heavy because it has new strong interactions, or because it couples to a new strong interaction sector. Such models can produce resonances that decay to $t\bar{t}$. These resonances could appear already above 1 TeV, although flavor constraints suggest masses of ~3 TeV.

If the top quark has new interactions, we will want to measure the pointlike current form factors of the top quark. These can be measured through FB and polarization asymmetries in $e^+e^- \to t\bar{t}$.

## angular distributions for asymmetries




t quark




b quark

Devetak and Nomerotski

And, in any scenario with a light Higgs boson, we will want to understand the properties of this particle with as much precision as possible.

The ILC must observe and measure all important decays of the Higgs boson.

In the reaction $e^+e^- \to h^0 Z^0$ $\qquad m_h = 120\ \mathrm{GeV}$ :

observe: $h^0 \to b\bar{b}, c\bar{c}, gg, \tau^+\tau^-, WW^*, ZZ^*, \gamma\gamma, \gamma Z$

with absolutely normalized branching ratios at % level of accuracy.

At 1 TeV, add the couplings $h^0 \to \mu^+\mu^-, t\bar{t}, h^0 h^0$

The tight focus of the GDE on 500 GeV is a disadvantage in the debate over the correct energy.   The question will always be raised:  Can we eventually go to higher energies ?

The GDE and its PAC should discuss a vision for later, higher energy stages of the ILC.   This could play out over decades. A model is the "site-filler" accelerator vision in the original proposal for Fermilab.

Mike Harrison discussed a staged approach to CLIC with ILC as the first stage.

Another possible vision is a plasma wake-field accelerator (which could have the same time structure) as an afterburner to ILC.

I conclude that, even if the LHC discoveries come only after 2013 and involve new particles above 1 TeV,

the ILC experimental program will be very rich and will directly address the crucial and urgent questions raised by the LHC.

As a member of the PAC, you need to think through these issues NOW and see if you agree.

If so, you need to push to GDE to be ready to propose the ILC in 2012.